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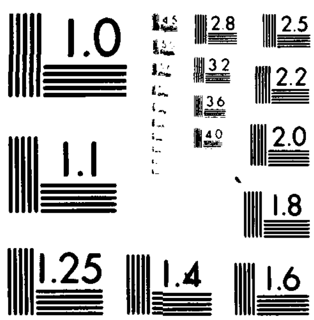

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PREDICTING FAILURE OF OPTICAL GLASS FIBERS

by

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Karl Jakus

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FOREWORD

This report describes the results of a research program oriented toward a better understanding of lifetime predictions for optical glass fibers. Some of the progress made toward this goal is summarized in the attached technical paper comprising this report.

"PREDICTING FAILURE OF OPTICAL GLASS FIBERS"

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Abstract

Factors that affect failure predictions of optical glass fibers in service were studied. These factors include the effect of various polymeric coatings on the fatigue behavior, dependency of long-term fatigue predictions on the form of the subcritical crack velocity, and prediction of long-length strengths from strength data of short-length specimens.

Introduction

One of the key problems in the design of a high-strength, optical fiber communication cable is the long-term mechanical reliability of the glass fibers. Unfortunately, glass fibers exhibit delayed failure (commonly known as static fatigue) and a wide variability in fracture strength that can cause a significant number of the fibers to fail at moderate stress levels. Realizing that these glass fibers can be subjected to tensile stresses in communication cables, it is important that the possibility of failure be statistically predictable.

The purpose of the present research was to study three factors that are important in predicting failure of optical glass fibers. These were: 1. measuring the effect that polymeric coatings can have on the fatigue resistance of the glass fiber, 2. determining which form of the subcritical crack velocity equation (power law or exponential) is best for long-term failure predictions, and 3. predicting long-length strengths from tensile strength data of short-length fibers.

Experimental Procedure

Three types of optical fibers were supplied by ITT Electro-Optical Division for experimentation. All fibers consisted of a doped fused silica core with a borosilicate cladding but each had a different polymer coating. The three polymer coatings were polyene/polythiol ester, urethane acrylate, and polyester elastomer.

The fatigue resistance of the fibers was measured in ambient air (23°C, 55% RH) by the dynamic fatigue technique where fracture strength is determined as a function of constant stressing rate in an Instron Testing machine using 0.1 m capstan grips and a gage length of 0.3 m. The strength data was fitted by least squares analysis to:

$$\ln\bar{S} = a_o + a_1 \ln \dot{\sigma} \tag{1}$$

where $\bar{S}$ is the median strength at a constant stressing rate $\dot{\sigma}$ and a_o, a_1 are regression constants. From fracture-mechanics theory the fatigue resistance parameter, N, is determined from:[1,2]

$$a_1 = \frac{1}{N+1} \tag{2}$$

Values of N for optical glass fibers have been previously found to range from 15 to 29 depending on the type of fiber and test conditions.[2,3]

Longer-term, static fatigue experiments using the polyester elastomer coated fiber were also carried out by measuring time-to-failure as a function of constant applied stress. The same gripping arrangement as in the dynamic fatigue tests was used to insure no grip failures. The gage length for these tests was 0.3 m and the constant stress was applied through a lever arm. The test environment was ambient air (23°C, 55% RH).

Results and Discussion

Fatigue Resistance of Polymeric Coatings

Table I summarizes the fatigue resistance of various polymeric coatings. It should be noted that the fatigue resistance of optical glass fibers coated with the polyester elastomer was measured several times in our laboratory utilizing both fibers that had been proof tested and that had not. In all cases "N" values ranged from 22-26 and this range is thought to be representative of the reproducibility of the experiment. From these results it is believed that the polyene/-polythiol ester coating results in a significantly higher fatigue resistance and the urethane acrylate coating a lower fatigue resistance. It is interesting to note that Krause and Carnevale[5] found from limited dynamic fatigue data that "N" varied from 17 to 24 for suprasil fused silica glass fibers coated with epoxy-acrylate, silicone/-nylon, epoxyl nylon, and hot melt/nylon.

The adhesive strength of the polymer to the glass is thought to be the major factor in determining the fatigue resistance of polymer coated, optical glass fibers as measured by dynamic fatigue technique. A polymer that bonds strongly to the glass surface could limit the availability of moisture and/or the OH-ion at the glass surface, thus reducing the amount of stress corrosion. The polyene/polythiol ester coating is known to have a strong adhesion to glass[6] and, in contrast, the urethane acrylate coating is known to bond weakly to glass.[7] The high fatigue resistance of the polyene/polythiol ester coating (N=34) and the low fatigue resistance of the urethane acrylate coating (N=18) are thus consistent with how these coatings adhere to glass. However, a model of the fatigue mechanism incorporating the role of the polymer coating has not been developed to date. This model would have to include how the polymer coating and its adhesion to glass could affect the fatigue process by limiting the availability of water at the glass interface.

Table I. Fatigue Resistance Parameter N of Polymer Coated, Optical Glass Fibers As Measured by the Dynamic Fatigue Technique in Ambient Air (23°C, 55% RH)

Coating	N	Reference
Polyene/Polythiol Ester[a]	34	This Study
Urethane Acrylate[b]	18	This Study
Polyester Elastomer[c]	22-26	This Study
Ethylene Vinyl Acetate	25	3
Polyene/Polythiol Ester	32	4

[a]W. R. Grace and Co., Columbia, MD 21044
[b]DeSoto, Inc., Des Plaines, IL 60018
[c]E. I. DuPont de Nemours, Inc., Wilmington, DE 19898

It is interesting to note that Kalish and Tariyal[3] found a dependence of fatigue resistance parameter N on the relative humidity of the test environment for optical glass fibers. They found that "N" as measured by the dynamic fatigue technique decreased from 29 at 2% RH to 25 at 45% RH to 16 at greater than 71% RH. By comparing these "N" values to those of the differently coated fibers from this study, the urethane acrylate coating corresponds to an "N" between those measured at 45 and 71% RH, and the polyene/polythiol ester to an "N" value greater than that measured at 2% RH. These comparisons are interesting because "N" values in both studies are thought to increase when moisture availability was restricted. In this study good adhesive bonding of the coating to the glass is thought to have limited the availability of moisture to the glass surface and in the study by Kalish and Tariyal the test humidity level controlled the moisture availability.

<u>Exponential vs. Power Law Form of the Crack Velocity Equation</u>

Because of the expense involved in long-term strength testing, it is valuable if long-term lifetime predictions can be made from relatively short-term, dynamic fatigue tests. A fracture mechanics based

theory[1,8] offers a framework within which these lifetime predictions can be made. Unfortunately, long-term failure predictions are quite sensitive to the assumed relationship between the subcritical crack velocity, v, and the stress intensity factor, K_I.[9,10]

Four subcritical crack velocity equations were considered in this study are:

$$v(K_I) = A_1 \ (K_I/K_{IC})^{n_1} \qquad \text{(Ref. 8)} \qquad (3)$$

$$v(K_I) = A_2 \ \exp[n_2(K_I/K_{IC})] \qquad \text{(Ref. 11 \& 12)} \qquad (4)$$

$$v(K_I) = A_3 \ \exp[n_3(K_I/K_{IC})^2] \qquad \text{(Ref. 13)} \qquad (5)$$

$$v(K_I) = A_4 \ (K_I/K_{IC}) \ \exp(n_4(K_I/K_{IC})^2) \qquad \text{(Ref. 14)} \qquad (6)$$

where K_I is defined as,

$$K_I = Y \quad \sigma \sqrt{a} \qquad (7)$$

and K_{IC} is the critical stress intensity factor, σ is the applied stress, a is the characteristic dimension of the strength controlling flaw, and Y is the flaw geometry factor. "A" and "n" are the material/environment fatigue constants to be evaluated by short term laboratory strength tests.

The basic differential equation that describes fatigue failure due to subcritical crack growth is obtained by differentiating Eq. (7) with respect to time to give:

$$v \ (K_I) = \frac{2K_I}{Y^2\sigma^2} \frac{dK_I}{dt} - \frac{2K_I^2}{Y^2\sigma^3} \frac{d\sigma}{dt} \qquad (8)$$

For static fatigue where $\sigma = \sigma_a$ = constant, Eq. (8) can be integrated to give the lifetime to failure, t_{fs}, as:

$$t_{fs} = \frac{2}{Y^2\sigma_a^2} \int_{K_{Ii}}^{K_{IC}} \frac{K_I}{v(K_I)} dK_I \qquad (9)$$

where K_{Ii} is the initial stress intensity factor. Upon substituting Eqs. (3) to (6) into Eq. (9), integrating and neglecting relatively small terms, one obtains four lifetime equations corresponding to the four crack velocity functions:[10]

$$t_{fs}\,\sigma_a^2 = \frac{2K_{IC}^2}{A_1 Y^2 (n_1 - 2)} \left(\frac{\sigma_a}{S_i}\right)^{2-n_1} \tag{10}$$

$$t_{fs}\,\sigma_a^2 = \frac{2K_{IC}^2}{A_2 Y^2 n_2} \exp\left(-n_2 \frac{\sigma_a}{S_i}\right) \left(\frac{\sigma_a}{S_i} + \frac{1}{n_2}\right) \tag{11}$$

$$t_{fs}\,\sigma_a^2 = \frac{K_{IC}^2}{A_3 Y^2 n_3} \exp\left[-n_3 \left(\frac{\sigma_a}{S_i}\right)^2\right] \tag{12}$$

$$t_{fs}\,\sigma_a^2 = \frac{2K_{IC}^2}{A_4 Y^2 n_4} \exp\left(-n_4 \frac{\sigma_a}{S_i}\right) \tag{13}$$

where S_i is the inert strength, i.e. strength measured in the absence of subcritical crack growth, and is defined as $\sigma_a(K_{IC}/K_{Ii})$. Once the fatigue constants A and n are determined, Eqs. (10) to (13) can be used for long-term predictions.

The fatigue constants can be determined from short-term dynamic fatigue tests where strength is measured as a function of constant stress rate ($d\sigma/dt = \dot{\sigma}$).[10] Under this dynamic loading condition Eq. (8) can be expressed as:

$$\frac{d}{dt}\left(\frac{K_I}{t}\right) = \frac{Y^2 \dot{\sigma}^2 v(K_I)}{2\left(\frac{K_I}{t}\right)} \tag{14}$$

Using the power law, Eq. (3), for $v(K_I)$, Eq. (14)[10] can be integrated to give lifetime under dynamic loading, t_{fd}:

$$t_{fd}\,S^2 = (n_1 + 1) \frac{2K_{IC}^2}{A_1 Y^2 (n_1 - 2)} \left(\frac{S}{S_i}\right)^{2-n_1} \tag{15}$$

where S is the fracture strength at constant stress rate. One may note from Eqs. (10) and (15) that the relationship between static and dynamic lifetime is:

$$t_{fd}\,S^2 = (n_1 + 1)(t_{fs}\,\sigma_a^2) \tag{16}$$

Unfortunately, with the exponential crack velocity equations, Eqs. (4)-(6), Eq. (14) can only be integrated numerically. The problem that arises is that numerical integration does not allow for least squares

fitting of the data to determine the fatigue constants A and n. Trantina[15] circumvented this difficulty by finding an approximate function to represent the results of his numerical integration for the exponential crack velocity equation represented by Eq. (4). He was then able to regress his dynamic fatigue data to get the fatigue constants. He did not extend, however, his approximate method to any of the other forms of the crack velocity equation.

The authors of this paper developed a numerical integration technique coupled with a non-linear regression analysis which makes it possible to evaluate the fatigue parameters A and n from dynamic fatigue data, irrespective of the form of the crack velocity equation.[16] With this computer data analysis technique, a set of parameters A and n are chosen and Eq. 14 is numerically integrated for each of the stressing rates used in the actual experiment to obtain the calculated median time to failure. The experimentally determined median inert strength is used in the the determination of the initial condition in these integrations. From the calculated and the experimental median time to failures at each of the stressing rates, a least squares sum is evaluated for the particular set of parameters A and n. The computation is then iterated with a new set of A and n until the minimum least squares sum is found.

The fatigue constants were obtained from dynamic fatigue data by the computer search technique for the polyester elastomer coated, optical fiber. Equations (10) to (13) were then used to predict static fatigue lifetimes that were then compared to actual experimental results, see Fig. 1. It is evident from Fig. 1 that any of the crack velocity equations can fit the dynamic fatigue data well in the data range; however, the predictions begin to diverge outside the data range. Looking at how well the predicted curves agree with the static fatigue data, it appears that the exponential forms of the crack velocity equation predicts the static fatigue data better than the power law form. Since all three of the exponential forms predict the static fatigue data equally well, it is not clear which of these would be more reliable for prediction to even longer times.

From the data presented in this paper, the danger in extrapolating experimental data is evident. Unfortunately, since any of the crack velocity equations can adequately represent the fatigue data in the range in which the data was collected, the form of the crack velocity equation becomes important only when the data must be extrapolated. To determine which form of the crack velocity equation best represents the fatigue data for a given material/environment system, it is recommended that data under different loading conditions (static and dynamic) be obtained and the crack velocity equation that best represents all the data be chosen for extrapolation. Through the use of the computer search technique discussed in this paper, the various crack velocity equations can be best fitted to the fatigue data and the most appropriate one selected. Finally, it should be recognized that the possibility of interfacial coating-glass interactions occurring and having adverse effects on long-term lifetimes has not been considered.[16,17]

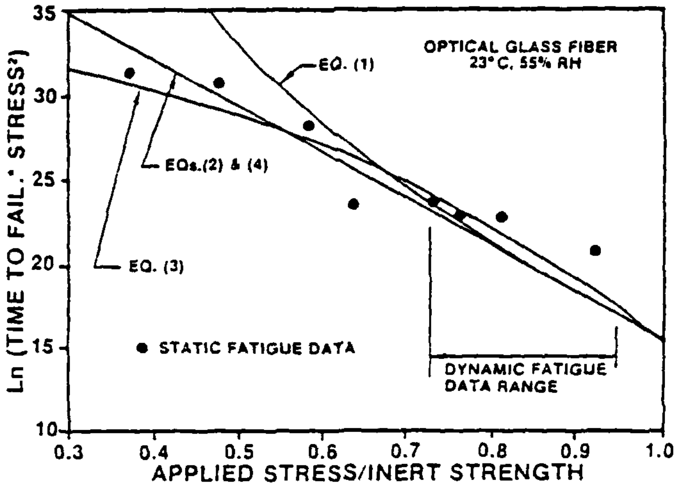

Fig. 1. Lifetime prediction diagram for optical glass fibers at 23°C, 55% RH based on the various subcritical crack velocity equations.

Predictions of Long-Length Strengths

The statistical analysis of fracture strength of optical glass fibers has generally followed the approach pioneered by Weibull[18] who showed that if a specimen of surface area A contains a statistical distribution of noninteracting flaws, the probability of failure (Φ) is determined from

$$1 - \Phi(S) = \exp\left[-\int_A dA \int_0^S g(S)\, dS\right] \tag{17}$$

where g(S) dS is the number of flaws per unit area with a strength between S and S+dS. Weibull then assumed an asymptotic functional form for g(S)

$$\int_0^S g(S)\, dS = \left(\frac{S-S_u}{S_o}\right)^m \tag{18}$$

where S_u is the lower limit in strength, S_o is the scale parameter, and m is the shape parameter. By assuming this function, Eq. (17) can be integrated and the distribution parameters S_u, S_o, and m can be deduced from strength-failure probability data. Kalish et al.[19] have applied the Weibull approach to strength data for optical glass fibers.

Unfortunately, real flaw distribution on optical glass fibers are not necessarily best characterized by Eq. (18) and a more fundamental approach to statistical analysis is preferred. Such an approach has recently been developed[20,21] and the analysis is quite straightforward for the uniaxial tensile test which is widely used for obtaining strength data for optical glass fibers.

In a uniaxial tensile test the specimen fails at the maximum stress, S_m, and Eq. 17 becomes

$$\xi (S_m) = - \ln [1 - \phi (S_m)] = A \int_0^{S_m} g (S) \, dS \qquad (19)$$

where A is the surface area under test and is equal tp $2\pi rL$ with r being the fiber radius and L being the gauge length. Differentiating Eq. (19) with respect to S_m gives

$$g (S_m) = \frac{1}{A} \frac{d\xi (S_m)}{dS_m} \qquad (20)$$

Thus, for uniaxial tension the flaw density, $g(S_m)$, at any stress, S_{m1}, is proportional to the derivative of the $\xi(S_m)$ curve at S_{m1}. Once $g(S_m)$ is determined, it can then be used to predict failure strengths for long length fibers as well as fibers under different modes of loading. For example, to make failure predictions for long length fibers in uniaxial loading, $g(S_m)$ is simply integrated using Eq. (19). For modes of loading other than uniaxial, where the stress distribution is more complicated, the integration equation becomes complex and the reader is referred to the paper by Evans and Jones[20] for example of cases where bending stresses are present.

Data analysis can be illustrated by examining data obtained for two groups (B and D) of optical glass fibers.[19] Both groups were drawn in an electric furnace and were polymer coated in line with the major difference being that Group D fibers were proof tested at 207 MPa. Group B fibers were tested with gauge lengths of 0.05 and 0.61 m and Group D fibers with a gauge length of 0.05 m. The numbers of samples tested in each data set was 270, 270 and 400, respectively.

The data analysis procedure first requires that the test data be ordered and then the cumulative failure probability $\phi(S_m)$ be determined as a function of the fracture stress, S_m. The quantity $\xi(S_m)$ [$\equiv -\ln[1-\phi(S_m)]$] is then evaluated and plotted as a function of S_m. A cubic polynomial is then fitted over the data and the derivatives of (S_m) that determine $g(S_m)$ can then be deduced directly from the polynomials. Fig. 2 shows an example of the flaw density curves for the 0.05 Group B.

To make strength predictions for long length fibers, the $g(S_m)$ distribution in Fig. 2 must first be extrapolated. It is evident from Fig. 2 that there is some uncertainty in extrapolating this distribution which leads to a predicted range in strengths. The extrapolation of the $g(S_m)$ function was carried out by extending the function from the data range to a strength level corresponding to about 100 MPa, after which the $g(S_m)$ function was extrapolated linearly to 0, 0. The $g(S_m)$ distribution could then be integrated using the trapezoidal rule over the strength range 0 to S_m. The predicted median strength [$\phi(S_m) = 0.5$] for a given long length was found by determining the strength value where the $\int g(S)dS$ function was equal to, see Eq. (19).

$$\int_{0}^{S_m} g\,(S)\,dS = \frac{-\ln\,(1 - 0.5)}{2\pi rL} \tag{21}$$

The results of the long length strength predictions are summarized in Table II. For comparison the predictions based on Weibull unimodal and bimodal strength distributions are also given in Table II.

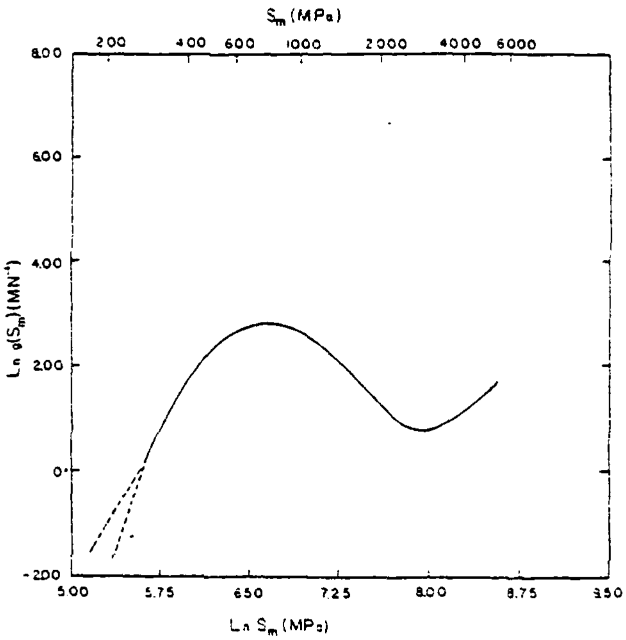

Fig. 2. Strength distribution function g (S_m) vs. fracture strength for 0.61 m group B fibers (data from ref. 19).

Table II. Comparison of predicted and actual fracture strengths at long lengths (L_2) for Φ = 0.50. Data from ref. 19.

Fiber data		Predicted strength at L_2 (MPa)			Actual strength at L_2 (MPa)
		Weibull unimodal	Weibull bimodal	Fundamental	
0.05 m Group B	498	2	203	169-213	179
0.61 m Group B	498	36	240	145-192	179
0.05 m Group D	1100	625	425	104-518	259

From Table II it is seen that the unimodal Weibull approach does not yield as accurate a failure prediction as the bimodal approach, as would be expected from this obviously bimodal data. The fundamental approach results in a failure prediction range that encompasses the

experimentally measured value. These predictions illustrate one advantage in using the fundamental approach. Namely, the unqualified use of Weibull statistics for data extrapolation can lead to a false confidence that the strength distribution parameters derived in one strength regime are pertinent to the entire population.[20,21] This difficulty is largely elimated with the fundamental approach since the strength range encompassed by the data is clearly indicated (Fig. 2) and the dangers inherent in extrapolating beyond the regime covered by the data become apparent. Also, the Weibull approach places unnecessary restrictions on the functional form of the distribution parameters. Although this problem can be partially counteracted by applying several piecewise Weibull distributions, this type of data analysis does not represent a realistic mixing of flaw populations.[21] This difficulty is largely eliminated by the fundamental approach.

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